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Principles of the Multiple Basic Index
System of Fire Danger Rating

by C. M. Countryman

The Nature of Fire Danger

Fire Danger Defined

What is fire danger? If this question was asked of a group of people concerned with the management of wildlands and their protection, we could probably get about as many different answers as there were people in the group. The owner of a wildland tract is likely to think of fire danger as indicating the probability of economic loss resulting from the cost of suppressing fire and the damage fire can cause. To the man charged with the protection of an area fire danger may well mean the chance of a fire starting and the difficulty of controlling any fire that does start. To the fire boss faced with a going fire the term will probably be associated with fire behavior, the rate of fire spread, the intensity of burning, the spotting probability--all the things that affect his job of suppressing the fire.

Fire danger is thus a very comprehensive term since it can include all aspects of fire behavior, fire control and fire effects. Inevitably, however, the manager of a wildland tract must finally be concerned with the damage that fire can do in the area under his management. It is this potential for fire to do damage that must ultimately control fire protection expenditures and determines the extent to which fire can be used as a tool in the management of the tract. In its broadest and most complete sense then, we may think of fire danger as the potential of fire to do damage in any area--a potential that is affected by such factors as weather, fuels, topography and economic values.

Despite the complex and somewhat abstract nature of this broad definition of fire danger some concrete evaluation of it is essential to wildland management. How much fire control effort is needed? Where should fire crews and equipment be located? What is the proper balance between manpower and equipment? What type and strength of prevention programs are needed? How should the daily initial attack strength be adjusted to fit daily variations in actual need? What differences in action are needed for fires starting at different times and places? How much damage will a fire do if no action is taken to suppress it? How much damage with varying degrees of control action? These are a few of the many questions and problems for which a measure of fire damage is needed.

The process of measuring or evaluating fire danger we call fire danger rating. These evaluations may be made on a numerical scale, by descriptive adjectives or a combination of both. Their basis may be either subjective or quantitative. If the danger rating system should take into account all of the factors affecting the potential damage to an area then the system can be said to rate total fire danger. If only part of the factors affecting damage are accounted for then the system is a partial evaluation of fire danger.

Present fire danger rating systems do not attempt to directly rate total fire danger. The large number and varied nature of the factors that affect damage from fire would of necessity require a complex system for their proper evaluation. The final answer would also need to be in economic terms since total fire danger is by definition the potential damage. Evaluations of certain phases of total fire danger, such as number of fires or rate of fire spread have been found to be of more value as a day-to-day aid in fire protection and use activities and these evaluations form the basis of most danger rating systems. These systems are thus partial evaluations of fire danger.

What is the relationship a partial evaluation of fire danger to total fire danger? To answer this question we need to look into the structure of fire danger.

The Structure of Fire Danger

The make-up of total fire danger can probably most easily be shown by diagrammatic analysis. Under this procedure fire danger can be broken down into smaller and smaller parts as desired with the relationship of each part to others and to total fire danger still easily apparent.

Fire danger has been defined as the potential of fire to do damage in any area. If we could know the number of fires that might be expected in any area and the damage that each fire would cause then the potential fire damage for wildland tract could readily be determined. Thus we can say that number of fires and damage per fire are the controlling components for total fire danger. This is shown diagrammatically in Fig. 1. Each of the controlling components can be broken down into smaller components.

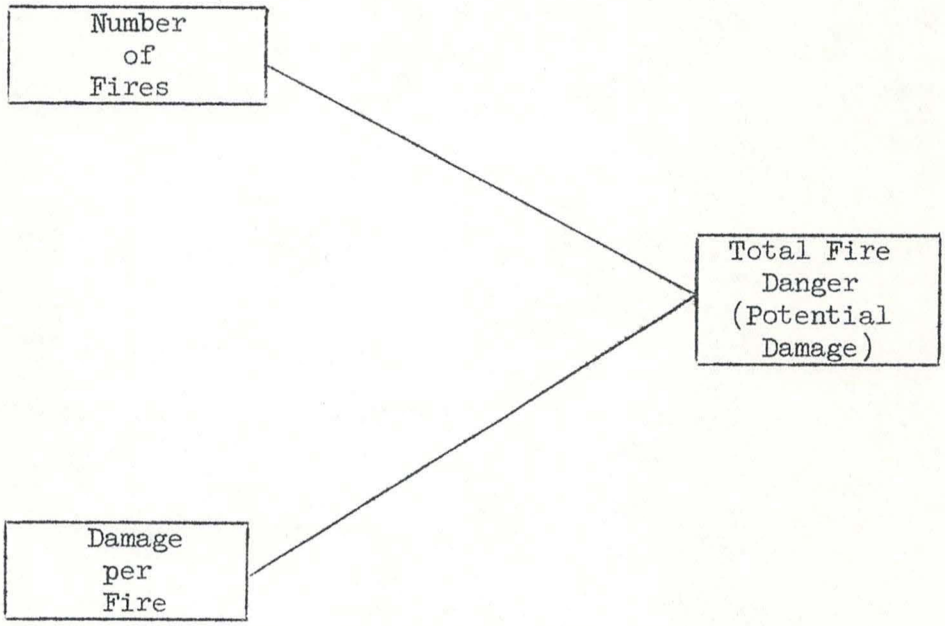

Figure 1. Structure of fire danger--controls of total fire danger.

Number of Fires

The number of fires in any area can be determined if we know but two facts; (1) the "risk," or how many firebrands are likely to be present in any area, and (2), the "ignition probability," or the chance that any given firebrand will actually start a fire if present. The risk for any area is governed by the frequency of man-caused fires and the frequency of fires from natural causes, such as lightning or spontaneous combustion. (Fig. 2).

Controlling ignition probability (Fig. 3) are the environmental factors of weather, fuel and topography. These include such items as wind speed, temperature, fuel moisture, fuel amount, fuel size, slope steepness, aspect, etc. Another group of controls on ignition probability is firebrand characteristics--size, shape, heat energy, whether flaming or glowing, etc.

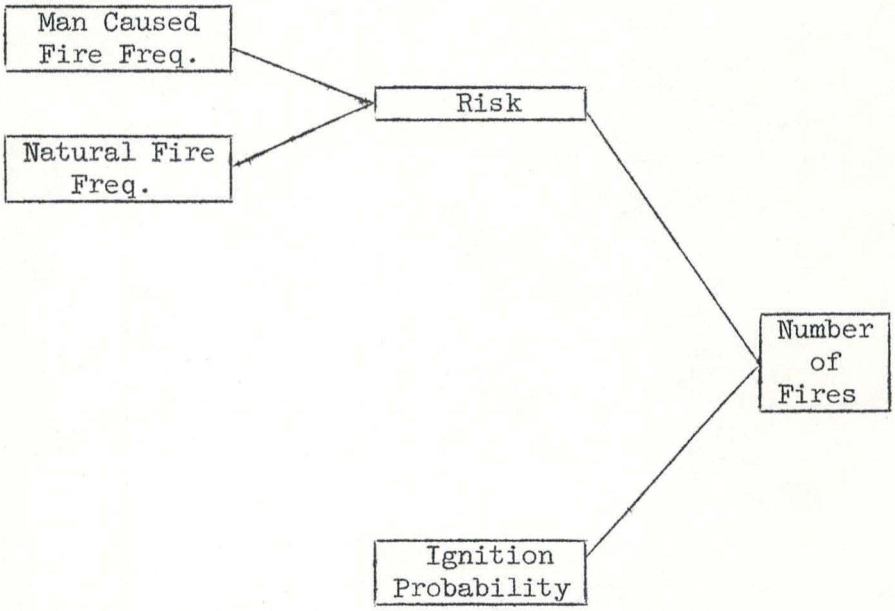
Man Caused Fire Freq.
Natural Fire Freq.
Risk
Number of Fires
Ignition Probability

Figure 2. Structure of fire danger--controls of number of fires.

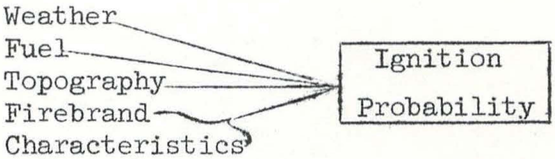
Weather
Fuel
Topography
Firebrand Characteristics
Ignition Probability

Figure 3. Structure of fire danger--controls of ignition probability.

Natural fire frequency is governed by the environmental factors (Fig. 4) but man-caused fire frequency is determined by the frequency of incendiarism and by the kind and amount of use the area gets--the "use load". In turn the frequency of incendiarism is controlled by the environmental factors and by the human quirks that make incendiarism possible. The environmental factors also frequently affect to a major extent the kind and amount of use made of an area and hence exert a control on the use load. The purpose of the use that is made of an area is sometimes a controlling factor also. For example, the use made of a railroad right of way is not greatly affected by environmental factors but is controlled primarily by the purpose of the use.

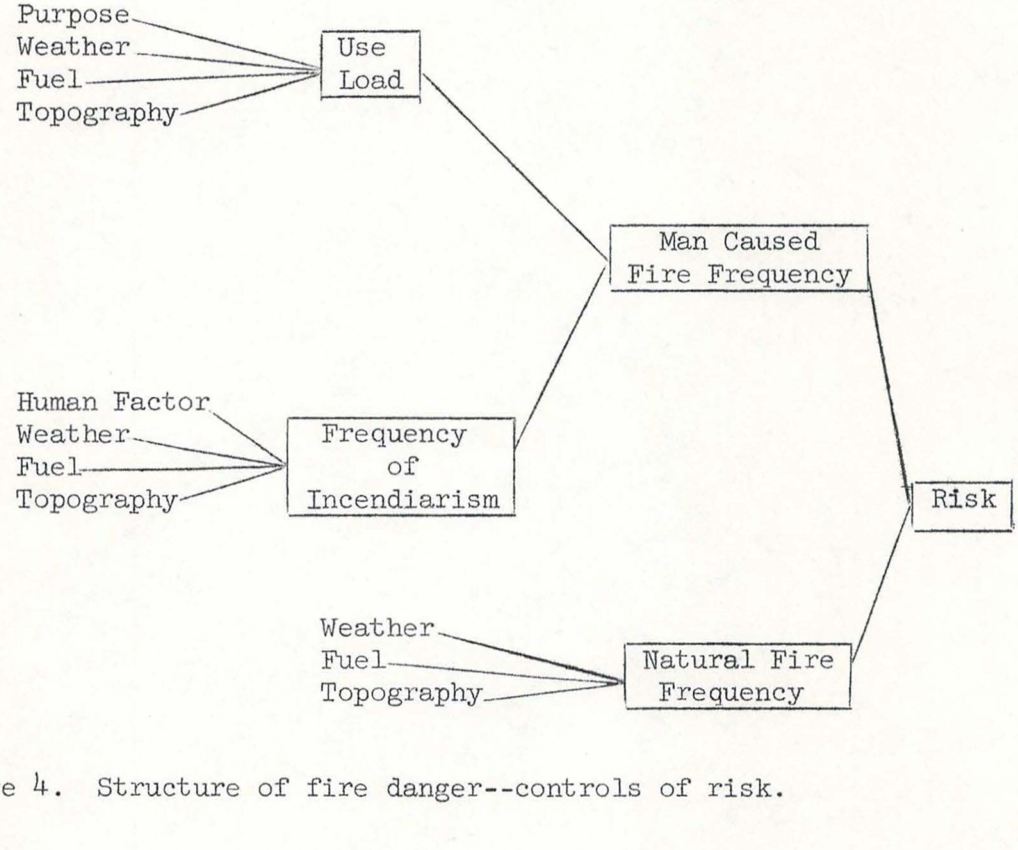
Purpose
Weather
Fuel
Topography
Use Load
Man Caused Fire Frequency
Human Factor
Weather
Fuel
Topography
Frequency of Incendiarism
Risk
Weather
Fuel
Topography
Natural Fire Frequency

Figure 4. Structure of fire danger--controls of risk.

Damage Per Fire

Turning now to the damage division of fire danger we find that we can determine the damage if we know the fire size and the damage per unit of area to the resource or values involved (Fig. 5). The resource damage rate can in turn be divided into two controlling components. These are susceptibility of the resource present to damage from fire and the rate of combustion[1] of the fire (Fig. 6). Rate of combustion plays an important part in the amount of damage since the hotter a fire burns the more complete the destruction is likely to be and the greater the damage per unit of area burned.

Continuing the analysis, (Fig. 7) the environmental factors, fire size, and rate of fire spread are found to control the rate of combustion. The susceptibility of the resource to damage (Fig. 8) is governed by (1) the resource type--range, timber, watershed, etc., (2) the kind of damage--burning, flood, erosion, etc., and (3), the resource location--on ridge, in canyon bottom, etc.

In appraising fire damage we are concerned with two different effects of fire size. It is readily apparent, all other things being equal, that the damage per fire must go up as the fire size increases simply because more of the resources becomes involved. In this case damage increases in direct proportion to the area burned. Size of the fire can affect indirect or intangible forms of damage in a different way. When fires are small damage to recreation and to esthetic values and damages from flood and erosion are usually small or negligible. Such damages, however, increase very rapidly as the fire size increases. For example, in a damage appraisal study in southern California[2] the expected flood and erosion damage in one watershed area when fires were 20 acres or less was estimated to be $3.70 per acre. Increase of fire size to 400 acres jumped the damage rate to $150 per acre, an increase of 40 times.

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[1] Rate of combustion refers here to the rate at which a given amount of fuel is burned and provides a measure of the heat output of the fire.

[2] Fire Damage From Increased Run-off and Erosion-Angles, Cleveland, Los Padres and San Bernardino National Forests, Buck, Charles C., Fons, Wallace L., and Countryman, C. M., California Forest and Range Experiment Station, 1948, 4 volumes.

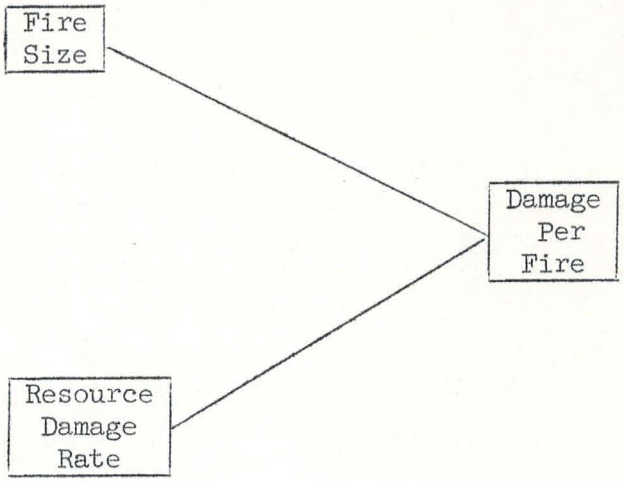
Fire Size
Damage Per Fire
Resource Damage Rate

Figure 5. Structure of fire danger--controls of damage per fire.

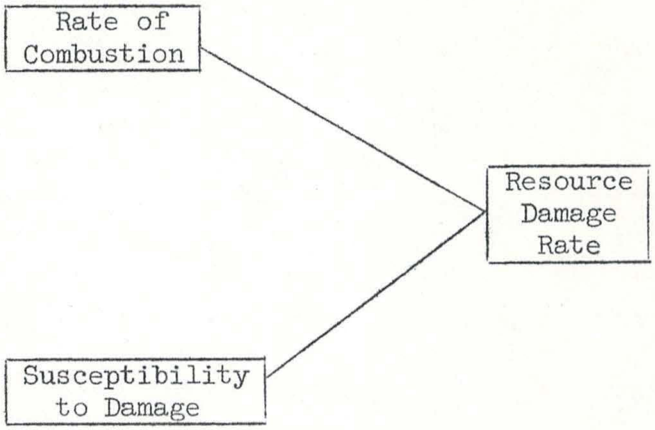
Rate of Combustion
Resource Damage Rate
Susceptibility to Damage

Figure 6. Structure of fire danger--controls of resource damage rate.

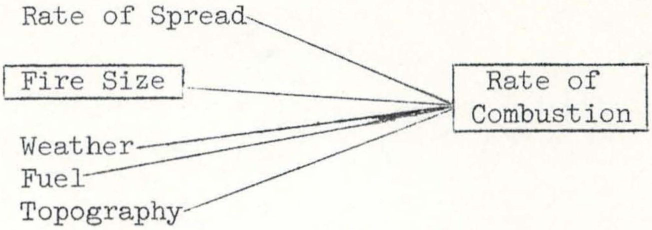
Rate of Spread
Fire Size
Weather
Fuel
Topography
Rate of Combustion

Figure 7. Structure of fire danger--controls of rate of combustion.

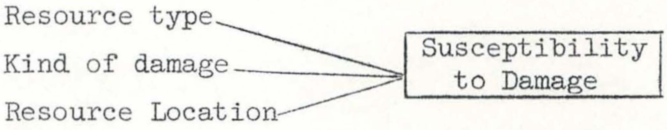
Resource type
Kind of damage
Resource Location
Susceptibility to Damage

Figure 8. Structure of fire danger--controls of susceptibility to damage.

Fire size can be broken down into two components that control its dimensions--rate of spread and burning time (Fig. 9). If we know how fast a fire will spread and the length of time that this spread is taking place, then the fire size can be determined. Rate of spread is controlled in turn by the broad group of environmental factors, by rate of spread, and also by fire size itself.

Taken all together the structure of total fire danger is shown in Figure 10. Note that fire size appears as a control of both rate of spread and of rate of combustion and that rate of combustion affects rate of spread and rate of spread affects rate of combustion. This situation arises because of the close interrelationship of fire size, rate of spread and rate of combustion. Change in any one of these components can cause change in the others. As will be shown later, this close interrelationship creates considerable difficulty in the development of simple danger rating systems.

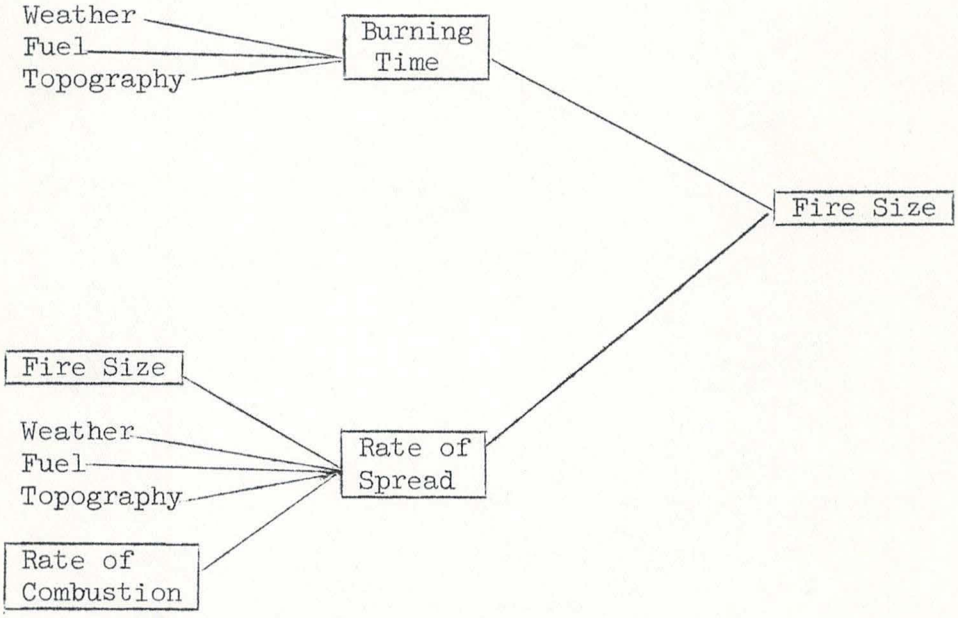
Weather
Fuel
Topography
Burning Time
Fire Size
Fire Size
Weather
Fuel
Topography
Rate of Spread
Rate of Combustion

Figure 9. Structure of fire danger--controls of fire size, burning time and rate of spread.

Items in boxes - Fire Danger Components
Items not boxed - Fire Danger Factors.

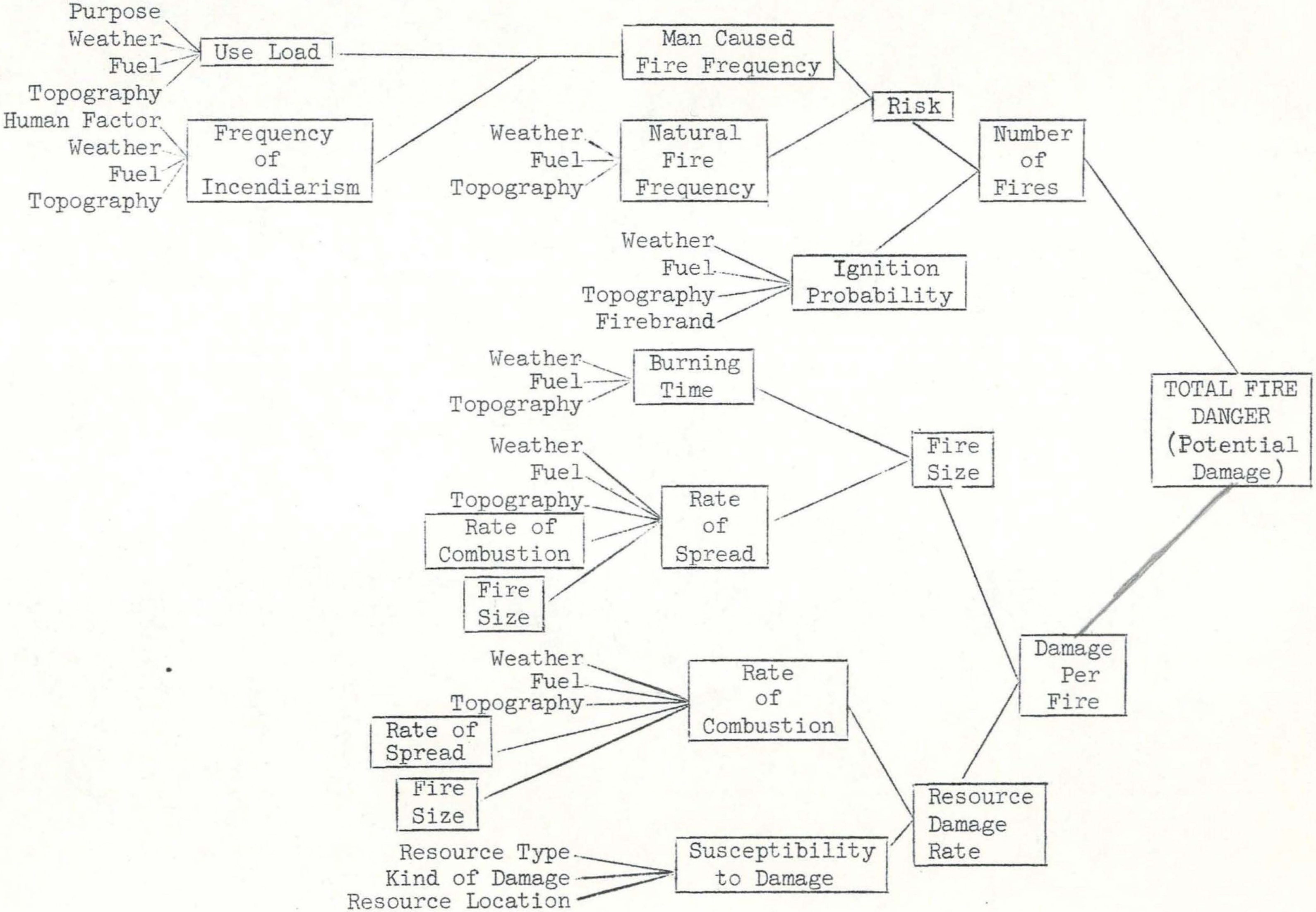
Purpose
Weather
Fuel
Topography
Use Load
Human Factor
Weather
Fuel
Topography
Frequency of Incendiarism
Man Caused Fire Frequency
Weather
Fuel
Topography
Natural Fire Frequency
Risk
Number of Fires
Weather
Fuel
Topography
Firebrand
Ignition Probability
Weather
Fuel
Topography
Burning Time
Weather
Fuel
Topography
Rate of Combustion
Fire Size
Rate of Spread
Fire Size
TOTAL FIRE DANGER (Potential Damage)
Weather
Fuel
Topography
Rate of Spread
Fire Size
Rate of Combustion
Damage Per Fire
Resource Type
Kind of Damage
Resource Location
Susceptibility to Damage
Resource Damage Rate

Figure 10.--Structure of fire danger.

Fire Control and Total Fire Danger

The preceding analysis was based on the proposition that no fire control action would be taken on any fire in the wildland area concerned. Fires were considered to be free to start, burn and spread until weather, fuel or topographic changes occurred that would cause the fire to go out. This assumption is necessary to obtain the true fire damage potential in any area. Where then does the fire control organization and fire control action fit into the picture?

Looking again at the structure chart (Fig. 10) we see that the diagram can be divided into two main branches. One branch is concerned with numbers of fires, the other with damage per fire. If no fires can occur, either because of no risk or no probability of ignition, then there can be no damage and no fire danger. On the other hand if fires can start but can do no damage because there are no values present to damage, or the fires do not spread, or do not burn with sufficient intensity to damage values present then again there can be no fire danger because there is no damage. In either of these events there is no need for fire control action or a fire control organization since such action or organization could not accomplish anything useful.

Taking a more practical view of the matter, however, we know that in our present society that the probability that no fires will start or that if fires do start that no damage of any kind will ensue is extremely remote. We know that for any sizable wildland area at least some fires are almost sure to start and are almost certain to cause some damage. The importance of this concept of the relation of fire control to damage is that the justification for fire control action lies in the prevention or reduction of fire damage. This is the sole purpose of fire control organization and action. If we accept this concept then we can also say that fire control can be justified only to the extent that it will reduce damage--that is, the cost of the organization and action cannot exceed the reduction in damage. It should be emphasized that this latter principle must not be interpreted as applying to damage that a fire does despite successful suppression action. Rather it is the damage that the fire would do if no action were taken that provides the justification for suppression costs. This same idea applies to prevention of fires as well. Thus it falls within the principle of reduction of damage to spend sums far in excess of damage actually caused to suppress a fire if by so doing greater loss would ensue if the action were not taken. From a practical point of view it is not possible to make this calculation for every fire controlled or prevented. In the long run for any given area, however, this must be the guiding principle in determining the amount of fire suppression and fire prevention that is justifiable.

The concept of damage as used here also must not be restricted to actual monetary loss. All forms of fire damage must be considered, both present and future. Indirect damages and damages to intangibles such as esthetic values for which no satisfactory method of direct monetary evaluation are presently available must be included. This is particularly true of public lands and public fire control agencies but cannot be neglected entirely on private lands either.

We can see where the fire control organization fits into the fire danger structure by again referring to the two main branches of our structure chart. Since one of these is concerned with number of fires, it is obvious that we are concerned here with prevention of fires. Various fire prevention programs are the principal tools that can be used for the reduction of risk. In the past these have been applied toward reducing the probability of man-caused fires. Thus we can devise prevention programs aimed at the reduction incendiarism and fires resulting from the use made of wildlands. More recently considerable attention has been paid to the prevention of lightning fires mainly in fundamental studies carried on by the Skyfire project.[3/] Although results of these studies have not reached the stage where practical application can be made the potential gain in the prevention of these fires is great because of the large proportion of fires caused by lightning.

Another phase of fire prevention that has received some attention in the past and is now coming more and more into the foreground is that of fuel modification. Note that fuel factors enter into every component of the number of fires branch either directly or indirectly. By modification of fuel we can reduce the probability of fires both in risk and probability of ignition. A common program along this line has been the felling of snags to reduce the number of lightning fires and the probability of additional fires caused by spotting from existing fires. Disposing of fine fuels where the risk is high is another effective program.

Fire prevention and fuel modification then are the two fire control activities which fit into the number of fires branch of fire danger. The amount of such activity justified is controlled by the amount it will reduce damage.

Fire suppression action enters into the damage branch of fire danger rating. By suppressing a fire the burning time will be reduced with consequent reduction in fire size and damage. Suppression action often acts to reduce rate of spread during the time the action is taking place and hence acts on fire size in this way. Reduced rate of spread also serves to reduce rate of combustion and fire damage.

3/ Project Skyfire, Barrows, J. S. 48th Ann. West. Forestry Conf. Proc., Western Forestry and Conserv. Asso. pp 55-56.

Fuel modification can also be used to reduce the amount of damage. Reduction in amount of fuel such as is done in slash disposal can materially reduce rate of combustion with a consequent reduction in the damage potential. Fuel modification to create firebreaks and to break up large blocks of continuous fuel as is being done in the Fuelbreak project[4/] in southern California is a means of reducing probable fire size. We can change the susceptibility of values to damage by restricting the type and construction materials of improvements and locating them in places least likely to be damaged by fire. As in the number of fires branch the cost of action taken to reduce damage must not exceed the amount the damage is reduced.

The Multiple Index Fire Danger Rating System

Now that we have dissected total fire danger into its various components and have considered the relationship of fire danger to fire control activities let us look more closely at the intricacies of the multiple basic index system of fire danger rating. Looking again at the structure diagram (Fig. 10) we see that some of the parts making up total fire danger are shown enclosed in boxes while others are not. There are some distinct differences in these two groups that make necessary their separation. For convenience in this discussion we will call those items in the boxes fire danger "components" and those items not boxed fire danger "factors".

Fire Danger Factors

As used in the diagram the fire danger factors are not individual but are actually groups of related factors. Thus weather is not a single factor but includes all aspects of weather that have an effect on fire ignition and fire behavior such as wind speed, temperature, humidity, air stability, etc. Among fuel factors are such items as amount, arrangement, size, chemical properties, and ratio of dead to living fuel.

[4/] Fuel Break, Jay R. Bentley, California Forest and Range Experiment Station, Sept. 1958, 16 pg.

An important characteristic of the fire danger factors is that the quantitative values assigned to their effect on fire danger is entirely dependent on the component of fire danger or facet of fire behavior that is being evaluated. Weather, for example, appears as a factor in several places in the diagram--in rate of spread, fire intensity, ignition probability, etc. At first glance this would seem to indicate that a single measure or index of weather would greatly simplify the evaluation of fire danger. However, both theory and research results indicate that each of the various weather factors do not carry the same relative weight when correlated with different facets of fire danger and fire behavior. It has been fairly well established that, within the common range of values, the rate of fire spread increases rapidly with increase in wind speed, usually as some power function. Exploratory research into the effect of wind speed on ignition where small firebrands are concerned indicate there is a positive effect of wind speed on ignition probability for low ranges of wind speed but that the effect becomes negative above some optimum level of wind speed, usually 4 or 5 miles per hour. The other factors in the weather group also affect fire spread and ignition differently. Thus weather is not an independent component of fire danger and the relationship of each weather factor to the particular facet of danger or behavior we are trying to evaluate must be determined. The same is true of other groups of factors affecting fire danger.

Fire Danger Components

In contrast to the fire danger factors the fire danger components are independent. The factors or other components controlling the value of a particular component carry the same weight wherever the component is used or for whatever purpose the measure is needed. For example, rate of spread is controlled by the same factors (Fig. 10) and the same relationships wherever it is used in fire danger.

The fire danger components are the basic units of fire danger. It is upon this concept of independent, basic measure of fire danger, each having a definite meaning and definite relation to the concept of total fire danger that the multiple basic index system is founded.

The fire danger components derived directly from the fire danger factors, such as rate of spread and ignition probability can be designed first order components and indexes developed to represent these components are first order basic indexes. Indexes derived from the first order indexes are designated secondary indexes.

Partial Evaluations of Fire Danger

In the previous discussion we have seen that fire danger is made up of a number of independent components. The dimensions of each of these components is determined either by their relation to other components or to certain factors affecting fire danger. The fire danger factors actually exert the basic control of fire danger, however, since their relationship to the components they control must be determined before the component can be used to evaluate other components further along the chain toward total fire danger. This concept of the relationship of fire danger factors to the fire danger components controlling fire danger is fundamental to any logical system of rating fire danger and is the foundation of the basic multiple index system.

In the ideal danger rating system an absolute measure of each of the fire danger components would be needed. To set up such a series of measures, however, would require the writing of the equation involving the relationships and interrelationships between all of the individual factors affecting fire danger and the various independent components of fire danger. Despite the considerable progress that research in fire behavior and fire control has made, to write such a series of equations is not possible now--in fact it is not possible to provide a complete, absolute prediction of even one of the basic components of fire danger.

This does not mean, however, that some evaluation of fire danger based on physically and mathematically sound concepts is not possible. Using index numbers and partial evaluations of the fire danger components very useful and accurate "ratings" or "indexes" of fire danger can be constructed with fire behavior and control knowledge presently available. Since these ratings cannot be complete and absolute measures of either total fire danger or its components certain restrictions must be placed on their interpretation and use. It is important that the fire control officer know what these restrictions are and what the rating means if he is to avoid using the rating for purposes that are not consistent with the actual meaning of the numbers derived.

Because the multiple basic index system is based on the fundamental structure of fire danger one of its principal characteristics is its sequential chain of fundamental relationships. Each relationship is put into its proper place in reference to others and to total fire danger. This principle applies whether only one fire danger factor is being evaluated or if the evaluation involves several factors in different branches of the basic structure. Knowing how each of the factors is related in the structure to each component of fire danger and how the components must be fitted together makes it possible to specify what any partial measure of fire danger means and how far along the chain any single relationship can be carried before some other relationship must be brought into the picture.

How this principle works can be illustrated by use of the fire danger structure diagram (Fig. 10). Suppose that we want to evaluate the effect of wind speed (one of the weather variables) on total fire danger. Looking at the number of fires branch of the diagram we find that by establishing the relationship between wind speed and use load and wind speed and frequency of incendiarism we can combine these relationships to obtain the effect of wind speed on man-caused fire frequency. By also obtaining the relationship between wind speed and natural fire frequency we can then have a measure of the effect of wind speed on risk. If the relationship between wind speed and ignition probability is known, then we can combine this effect with the effect of wind speed on risk to get an evaluation of the effect of wind speed on number of fires. Before we can get the effect of wind speed on total fire danger we must determine the effect of wind speed on damage per fire by first establishing its relationship to each of the components it affects in this branch of the structure.

Note that in developing the evaluation of wind speed on total fire danger that as we moved along the sequential chain of relationships it was necessary to bring in the effect of wind speed on all of the components controlling the next danger component before proceeding. Hence it was necessary to have the relationship of wind speed to both man-caused fire frequency and to natural fire frequency before the effect of wind speed on risk could be determined. To fail to do this would result in an incomplete evaluation.

When only a partial evaluation of total fire danger is made, it is necessary to assume that all factors not included must remain at some constant value as the factors used in the evaluation vary. Thus in the example used above all of the weather factors except wind speed as well as all of the other groups of factors remain at some constant level when the relationship of wind speed to each of the fire danger components is determined. Partial evaluation of fire danger thus evaluates only that part of fire danger that is controlled by the factors included as variables in the system.

The fire danger structure diagram shows the way the fire danger components must be combined to evaluate total fire danger either partially or completely. It is not necessary, however, to carry the evaluation this far. For many uses of danger rating a partial evaluation of one of the components of fire danger is all that is needed to do a specific job. In setting up such an index care must be taken to include all preceding components in the evaluation. For example, the effect of fuel size on ignition probability could be made with the development of only one relationship, that of fuel size and ignition. An index of the effect of fuel size on risk, however, would require that the relationship of fuel size to use load, to frequency of incendiarism, and to natural fire frequency be developed as well.

When not being used to evaluate total fire danger, the danger components may also be combined in different ways than shown in the diagram in order to best fit a specific need. It is necessary, of course, that the combination be logical and the dimensions of the resulting combination be proper. The extent to which any partial index can be applied in evaluation of fire danger is thus limited by the fundamental relationships upon which it is based. Failure to recognize this limitation is one of the most common errors in both development and application of fire danger rating indexes.

Building a Multiple Index System of Fire Danger Rating

In order to illustrate the rules and principles involved in fire danger rating and the problems that must be solved in the development of a system and its use, we will go through the process of building a multiple index system. Because of lack of basic information we are limited to partial evaluations of fire danger. This means that there are numerous ways a danger rating can be put together depending upon which components are to be included in the rating or index. The principles are the same in all cases, however, no matter what form the final result may take.

The derived relationship between any fire danger factor and fire danger component simply describes the effect that factor has on the part of fire danger the component represents. The relationship provides information--it does not necessarily tell how this information can be used. To make practical use of the information the land manager must often know what effect variations in the component is going to have on fire protection needs, fire use, or other specific purpose. The real purpose of partial rating of fire danger is not just to provide information about variation in the component but rather to provide the land manager with guides to action as the variations take place. The danger index is hence an interpretation of the effect of the fire danger components on the different aspects of fire protection and fire use. These guides, not the basic relationships, become the fire danger rating. In any partial evaluation of fire danger, then, the purpose or use of the index to be derived is of primary importance in determining what factors and components must go into the system and how the different components should be combined.

One of the most common present day uses of fire danger rating is as a guide to adjust the day to day amount of fire control force needed to meet set burned area, or more accurately damage, objectives with changes in burning conditions. Since the fire control organization has already been established we can assume that at least a subjective evaluation of total fire danger has been made so that the basic organization strength is just sufficient to meet initial attack fire control objectives when burning conditions are at some predetermined level. If burning conditions are "easier" than this fixed level then the strength of the organization is greater than needed for the existing fire potential and the potential control cost will be excessive. Savings could be effected if the strength of the organization could be temporarily reduced to that actually needed. On the other hand, if burning conditions are more severe than those for which the basic organization was designed then the burned area objective cannot be met and damages will become excessive. Temporarily increasing the strength of the organization to that actually needed should bring costs and damages back into the desired balance again. The index that is needed for our specific purpose is one that will give a measure of the day to day change in the probable size of the control job that the fire control organization will face.

With the objective of the danger rating set the next step is to select the components of fire danger that must be included in the danger rating to fulfill the objective. Since we are interested in the daily variation in the magnitude of the fire control job, an evaluation of probable number of fires is an obvious need. All fires, however, do not require the same control effort, hence a measure of the job load for a fire burning under the various burning conditions likely to be encountered is necessary. For a fire burning under any given set of environmental conditions, the amount of effort needed to control it within a predetermined size will depend on how fast the fire is spreading and on the rate of combustion. As the rate of spread increases the time available for control becomes less and more control force must be available. Also as the heat output (rate of combustion) of a fire goes up the difficulty of control also increases.

To accomplish the objective of our fire danger rating then we must have evaluations of the effect of number of fires, rate of spread and rate of combustion on the size of the fire control job. These evaluations must be combined into a single index.

A major consideration in developing any danger index for general field use is that it be relatively simple and require a minimum of computations and field measurements in actual use. This usually means that only a few of the relationships of the fire danger factors to fire danger can ultimately be used in the final index. Since we are concerned in the index we are developing with day to day changes in the fire potential, we will be concerned mostly with the environmental factors that are the chief causes of these changes. Looking at our fire danger structure diagram (Fig. 10) we see that these factors are involved in all of the fire danger components with which we are concerned. Obviously we cannot meet the requirement for a simple system if so many relationships are to be included. The next step in the development of the system then is to find acceptable ways of reducing the number of relationships and still maintain the principal objective of the danger index. One way to do this is to select for inclusion in the index the factors causing most of the variation in the component being evaluated. The procedure, however, immediately introduces a limitation on the accuracy and interpretation of the index. For each factor that is omitted we introduce error into the system in direct proportion to the amount of control the factor or component actually has. Although other factors than those selected do not appear directly as variables in the index it is impossible to ignore them completely. When we select the factors to use as variables, we then automatically specify that the other factors are considered at some constant level.

This cannot be avoided. If experimental procedures are used to develop the relationship between the selected factors and the fire danger component, the experiment is set up so that all factors except the one being evaluated is held constant while the factor is varied over the range of its expected values. With this method the conditions under which the fire danger component is evaluated are known and can be fixed at some specified level.

If empirical data are used, such as would be the case when the relationships are derived from fire and weather reports or uncontrolled tests, each of the factors not being evaluated automatically take on a value equal to the average of all their individual values in the population of data actually used in developing the relationships. In this case the constant values are usually not known.

When we select the factors to be used as variables in an index, we automatically also define the meaning of the index. For example, if we select wind speed and fuel moisture to determine rate of spread, then the resulting index is an evaluation of wind speed and fuel moisture on rate of spread only. It is an absolute measure of rate of spread only when the other factors, such as topography and fuel characteristics, are at the constant level specified. When conditions vary from this level, then the index must be in error to some degree. In selecting which factors to use as variables and which to specify as constant we must select them so as to reach an acceptable balance between rating system complexity and system accuracy. As a general rule the fewer the factors and components included as variables in the system, the less accurate and flexible is the rating system. The price we pay for increased accuracy in danger rating is more complexity.

This technique of specification is an extremely useful tool in developing fire danger indexes. In fact, fire danger rating with our present level of quantitative knowledge of fire behavior factors and wildland environmental factors would not be possible at all without it. All existing danger rating systems make extensive use of the procedure. We know that weather and fuel factors vary widely in time and space both horizontally and vertically. In measuring fire weather, for example, we specify the conditions under which it is to be measured. Wind is measured at some specified height, usually 20 feet above open level ground or its equivalent. Temperature and humidity are measured in a shelter at a standard height of $4\frac{1}{2}$ feet. Fuel moisture is often measured by use of a specified indicator stick placed at a specified height and exposure conditions. The whole fire weather station is arranged in a specified manner and with a specified exposure. Observations are made at specified times.

As long as the fire weather observations are made according to specifications, the observations measure the relative change in weather and fuel moisture from time to time. The observations are valid absolute measures, however, only for the specified conditions at which they were made. Thus at some instant we may measure a wind speed of 15 m.p.h. at 20 feet above the gound. At the same instant the wind speed at 5 feet may be only 8 m.p.h. It is important to remember in fire danger rating and in other fire control operations that weather information is absolute data only for the specific situation under which it was measured or for which it was predicted and is only indicative for situations that deviate from those specified.

Returning again to the fire danger structure diagram let us see what we can do with this specification tool to simplify setting up our index of daily variation in the fire control job. Consider first the number of fires branch of the diagram. Because of the large element of chance in fire occurrence the fire control organization must be prepared to cope with at least one fire a day--except when the fire probability is zero. If the risk is great then the organization must be strong enough to take care of more than one fire at the same time. In some areas the variation in risk day by day is great enough to justify the inclusion of risk in the index. More frequently risk is largely dependent on chance, or on variations in use such as occurrence of holidays, hunting seasons, etc. For these reasons it is usually more practical to consider risk independently in its effect on fire control. For the purposes of this discussion, we will hence specify risk as constant in our index. The variation in number of fires will then depend only on ignition probability. The fire danger components we need to evaluate in our index then is reduced to ignition probability, size of fire, rate of spread, and rate of combustion.

Earlier it was pointed out that the close interrelationship of rate of spread, rate of combustion and fire size creates considerable difficulty in setting up a simple danger rating system. Since variation in any of these components causes changes in the others, the equations for determining the relation between any of these components and the factors controlling them become very complex and would require procedures too complicated for day to day field computation. Considerable simplification could be achieved by elimination of fire size from consideration. Since our index is being set up for an existing control organization, we can assume that some conditions must have been specified when the organization was established. One of these would be the burned area objective. This is usually expressed as allowable fire size. The allowable fire size is usually relatively small. One use of the index would then be to provide a guide to the size of the organization needed to permit control of all fires at less than this specified size despite changes in burning condition. We are thus concerned primarily with fires when still small enough to be susceptible to control with initial attack procedures. Because the effect of fire size on spread and combustion rates is relatively minor when a fire is still small, we can specify fire size as "small" and treat it as a constant without much loss in accuracy in our danger rating index. The number of fire danger components with which we must be concerned has now been reduced to three--rate of spread, rate of combustion and ignition probability.

Consider first the rate of spread component. For rate of spread we need to determine the relationship of weather, fuel and topographic factor groups and also the rate of combustion component to rate of spread. The topographic factors and many of the fuel factors have little timewise variation. The weather-fuel interrelationship of fuel moisture is the chief exception. Since our index is concerned primarily with the changes in the job load in short time periods, these factors could be specified at some constant level with relatively little loss in the temporal evaluation of job load. This would leave only weather, fuel moisture and rate of combustion to be considered. While there are a large number of weather factors that affect rate of spread, experience and research have shown that wind speed is probably most important timewise. Some of the other factors, such as relative humidity and temperature, have a direct effect on fuel moisture and hence are automatically partially evaluated in the measurement of fuel moisture. Except for rate of combustion then we have only to develop the relationship of wind speed and fuel moisture to rate of spread to set up an index of rate of spread.

Looking now at rate of combustion let us consider first what makes it vary. Rate of combustion was defined as the rate at which fuel burns. Variations in this rate can occur if; (1) there are differences in the amount of available fuel per unit of area; (2) if the fuel available burns more quickly or slowly; or (3) if the fire moves more rapidly or slowly across an area. The last possibility, of course, is synonymous with rate of spread. The second possibility also must bring about change in rate of spread. These two causes of changes in rate of combustion then must vary in the same direction and with rate of spread so that they can be evaluated by rate of spread.

The first possibility can occur in two ways. The most obvious is a difference in the physical amount of fuel on an area. The second way is for a change to take place in the amount of fuel that actually burns. This latter effect can be brought about by changes in the moisture content of the fuel. In a fuel bed composed of a mixture of various sized fuels the small fuels and surface of large fuels dry out and become burnable first. As the drying process continues more and more of the larger fuel becomes available for burning in time to add to the peak heat output of the fire. The increase in rate of combustion from this cause may have a positive or negative effect on rate of spread depending upon specific conditions of the fire area and level of the combustion rate. This characteristic of combustion rate then becomes an independent control of rate of spread.

Although some simplification was achieved in the system by considering size of fire a constant the close interrelationship of rate of spread and rate of combustion still leads to a complex system. The problem is further complicated by the fact that both components affect the size of the control job but not necessarily in the same manner. In an index combining both components the same index number can be obtained with different combinations of the components. That is, a high rate of spread index and low rate of combustion can produce the same index number as a high rate of combustion and low rate of spread. The fire control job in these two situations are not the same, however. While it is possible to combine the two components and their individual effects on the size of the control job into a single equation the computational procedures needed would be too complex for general field use. We could simplify the procedure if some way could be found to separate the components and determine their effect on the control job separately. The individual effects then could be put together more easily, to give the combined effect of the components on the fire control job.

The key to this separation lies in the effect that fuel and fuel moisture have on rate of spread and rate of combustion. Previously it was shown that for rate of spread we can specify fuel type as being constant without much temporal loss in accuracy. It is also feasible to extend this constant fuel type assumption to the determination of rate of combustion as well, thus permitting us to eliminate the effect of physical differences in the amount of fuel available from direct consideration in the system.

Consider for the moment that our specified fuel type is made up of fine fuels only such that any fire will burn all of the fuel completely. In this case rate of combustion would vary only with rate of spread and one index would serve to evaluate both. This is the situation that would occur in many grass fuel types.

If the specified fuel type is the more common mixture varying from fine to large materials, the effect on rate of spread and rate of combustion of the varying fuel availability due to the moisture content of the larger materials must be taken into account. "Fine fuel moisture," as used in fire danger rating, usually refers to the moisture content of the small sized fuels and also to the surface layer of large fuels and ground litter. These fine fuels can change in moisture content very quickly in close accord with changing environmental conditions. In contrast the deeper layers of fuel vary much more slowly with changes taking place over days or weeks. All other factors being equal we can then expect the fine fuel moisture to exert primary control on the more rapid fluctuations in rate of spread and on variations in rate of combustion affected by rate of spread. The change in amount of available fuel brought about by the variation in the moisture content of the "heavy" fuels will control the slower variations in rate of combustion and the changes in spread rate controlled by the variations in rate of combustion.

This difference in effect of fine fuel moisture and heavy fuel moisture provides a convenient means of separating the effect of rate of spread and rate of combustion on the fire control job. Our rate of spread index based on wind speed and fine fuel moisture also provides an index of the associated inseparable changes in rate of combustion. A rate of combustion index based on moisture content of heavy fuels only can be used also to evaluate the effect of this variation on rate of spread.

In most natural fuel beds there is usually no sharp distinction between fine fuels and heavy fuels since the graduation from the smallest to largest or deepest layers is continuous. The fine fuel moisture content used for the rate of spread index should be representative of enough fuel sizes so that a fuel bed comprised only of these sizes would in their natural arrangement provide for continuous fire spread. The maximum fuel size for this purpose is dependent upon fuel type and can be highly variable from region to region but ordinarily would not exceed fuels more than one-half inch in diameter or one-fourth inch deep layer of the larger fuels and litter.

Where there is a wide range of fuel sizes it is sometimes desirable to divide the heavier fuels into two or more size classes because of the great variability in the rate of moisture change in these fuels. In the combustion rate index these fuel classes can be weighted according to their relative effect in the fuel complex being considered.

The place of living fuel moisture in the rate of spread index and rate of combustion index is dependent upon fuel type. Where fine living fuels are closely intermixed with fine dead fuels the effect of the moisture content of these fuels on fire spread must be included in the fine fuel moisture values used. Usually, however, the effect of fine living fuels when they comprise less than twenty percent of the total fine fuel amount can be neglected with little loss in accuracy of the index. Where these fuels are annuals or gradually die and cure during the fire season the variability in their moisture content over the season must be included in the moisture content evaluation. In some fuel types such as western chaparral, the effect of living fuel moisture is reflected mostly in rate of combustion over much of the fire season, hence the moisture content of these fuels are best included in the rate of combustion index.

It must be recognized that the rate of spread and rate of combustion indexes are not complete indexes of either facet of fire behavior. The rate of spread index does not include the effect of combustion rate controlled by heavy fuel moisture while the combustion index does not include the effect of spread rate on rate of combustion. In effect the spread index indicates the relative rate of spread at some constant heavy fuel moisture content or combustion index and the combustion index indicates the relative rate of combustion at some constant rate of spread. This property of the indexes is not of concern in our fire danger rating which is a measure of the size of the fire control job, since the two indexes are used only as steps in arriving at the final index. It does impose restrictions on the interpretation and use of the individual indexes for other purposes, however. The procedure has the advantage of greatly facilitating the computation of the danger index we are developing.

The way in which the separate indexes can be used operationally in computing fire danger is illustrated in Tables I, II and III. Table I is an index of relative rate of spread using wind speed and fine fuel moisture. In Table II two classes of heavy fuel moisture are combined to give a relative combustion rate index. These two indexes are combined in Table III to give a measure of the size of the control job as affected by these two facets of fire behavior. It should be emphasized that the values in the body of this table represent the relative size of the control job at different levels of spread and combustion rate and not a measure of fire behavior. Each horizontal line in the table then represents the change in the control job at a constant combustion rate but with varying rate of spread and each vertical column the change in job load at a constant spread but varying combustion rate. In order to set up this table the relationship of the size of the control job as related to the spread index and to the combustion index must be developed independently. For convenience in further discussion the control job index shown in Table III will be designated as a "Burning Index".

TABLE I

SPREAD INDEX[1] ← Perimeter increase

Fine fuel moisture	Wind speed (m.p.h.)																
	00	03	06	08												22	
	02	05	07	09	10	11	12	13	14	15	16	17	18	19	20	21	23	24+
1.5	14	19	23	28	33	37	40	43	47	51	55	61	66	70	74	83	89	100
2	13	17	21	26	30	34	37	40	43	47	51	56	61	65	70	77	82	92
2.5	12	15	20	24	28	32	35	38	41	44	47	52	56	61	67	72	77	86
3	11	14	18	22	26	29	32	34	38	41	44	48	52	57	62	67	73	81
4	10	13	16	20	23	26	29	31	34	37	39	43	47	51	56	60	64	72
5	8	11	14	17	20	22	25	28	30	33	35	38	41	45	49	53	57	62
6	7	9	12	14	17	19	21	24	26	28	30	33	35	39	44	47	49	54
7	6	8	10	12	15	17	19	21	22	24	26	29	31	33	39	42	44	46
8	5	7	9	11	13	14	16	17	19	20	22	25	26	29	33	36	38	41
9	5	6	7	8	10	11	13	14	16	17	18	21	22	25	28	30	32	36
10	4	5	6	7	8	9	10	12	13	15	16	17	19	20	24	25	27	29
11	3	4	5	6	7	8	9	9	11	12	12	13	15	16	19	20	22	24
12	2	3	3	4	5	6	6	7	8	9	9	10	11	13	14	15	16	18
13	1	2	2	3	3	4	4	4	5	6	6	7	8	9	10	11	12	13
14	0	0	0	0	0	1	1	2	3	3	4	4	5	6	7	7	8	8
15	0	0	0	0	0	0	0	0	0	0	1	1	1	2	3	4	4	5
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
18+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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[1] Adapted from "Wildland Fire Danger Rating" Pacific Southwest Forest and Range Experiment Station.

TABLE II

RATE OF COMBUSTION INDEX[1/]

Medium Fuel Moisture Content	Heavy Fuel Moisture Index										Fuel Stick Moisture Content
	000.0 001.9	002.0 003.9	004.0 006.9	007.0 010.9	011.0 016.9	017.0 025.9	026.0 039.9	040.0 061.9	062.0 099.9	100.0 200.0	
01.0	57	62	67	71	76	81	86	90	95	100	01.0
01.5	54	60	64	68	73	78	83	87	92	97	01.5
02.0	51	56	61	65	70	75	80	86	89	94	02.0
02.5	49	53	58	63	67	72	77	82	87	91	02.5
03.0	46	51	56	60	65	70	75	79	84	89	03.0
03.5-04.0	44	49	53	58	62	67	72	77	82	86	03.5-04.0
04.5-05.0	40	44	49	54	58	63	68	73	78	82	04.5-05.0
05.5-06.0	36	40	45	50	54	59	64	69	74	78	05.5-06.0
06.5-07.0	32	37	42	46	51	56	61	65	70	75	06.5-07.0
07.5-08.0	30	34	39	44	48	53	58	63	68	72	07.5-08.0
08.5-09.5	26	31	35	40	45	49	54	59	64	69	08.5-09.5
10.0-12.0	23	27	32	37	41	46	51	56	61	65	10.0-12.0
13.0-16.0	19	24	28	33	38	42	47	52	57	62	13.0-16.0
17.0-20.0	16	20	25	30	34	39	44	49	54	58	17.0-20.0
21.0+	13	17	22	27	31	36	41	46	51	55	21.0+

[1/] Adapted from "Wildland Fire Danger Rating" Pacific Southwest Forest and Range Experiment Station.

TABLE III

BURNING INDEX[1]

Com- bustion Index	Spread Index																							
	0	3	5	7	9	11	13	15	17	20	23	26	29	32	35	40	45	50	55	61	68	75	82	91
	2	4	6	8	10	12	14	16	19	22	25	28	31	34	39	44	49	54	60	67	74	81	90	100
0-12	0	0	1	1	1	1	2	2	2	2	3	3	4	4	5	5	6	6	7	8	9	9	10	11
13-19	0	1	1	2	2	2	3	3	4	4	5	5	6	7	7	8	9	10	12	13	14	15	17	19
20-26	0	1	1	2	3	3	4	4	5	6	6	7	8	9	10	11	13	14	16	17	19	21	23	26
27-32	1	1	2	3	3	4	5	5	6	7	8	9	10	12	13	14	16	18	20	22	24	27	30	33
33-36	1	1	2	3	4	5	6	6	7	8	10	11	12	14	15	17	19	21	24	26	29	32	35	39
37-39	1	2	2	3	4	5	6	7	8	9	11	12	14	15	17	19	21	23	26	29	32	35	39	43
40-42	1	2	3	4	5	6	7	8	9	10	12	13	15	16	18	21	23	25	28	31	35	38	42	47
43-46	1	2	3	4	5	6	7	8	10	11	13	14	16	18	20	22	25	28	31	34	37	41	45	50
47-49	1	2	3	4	5	6	8	9	10	12	14	15	17	19	21	24	27	30	33	36	40	44	49	54
50-52	1	2	3	5	6	7	8	9	11	13	15	16	18	20	23	26	29	32	35	39	43	48	52	58
53-56	1	2	4	5	6	7	9	10	12	14	16	18	20	22	24	27	31	34	38	42	46	51	56	62
57-59	1	2	4	5	7	8	9	11	12	14	17	19	21	23	26	29	32	36	40	44	49	54	59	66
60-62	1	3	4	5	7	8	10	11	13	15	18	20	22	24	27	31	34	38	42	47	52	57	63	69
63-66	1	3	4	6	7	9	10	12	14	16	18	21	23	25	28	32	36	40	44	49	55	60	66	73
67-69	1	3	4	6	8	9	11	13	15	17	19	22	24	27	30	34	38	42	47	52	58	63	70	77
70-72	1	3	5	6	8	10	11	13	15	18	20	23	26	28	32	36	40	44	49	54	60	66	73	81
73-76	1	3	5	7	8	10	12	14	16	18	21	24	27	29	33	37	41	46	51	56	62	69	76	84
77-79	1	3	5	7	9	11	12	14	17	19	22	25	28	31	34	38	43	48	53	59	65	72	79	87
80-82	1	3	5	7	9	11	13	15	17	20	23	26	29	32	36	40	45	50	55	61	68	75	83	91
83-86	2	3	5	7	9	11	13	15	18	21	24	27	30	33	37	42	47	52	58	64	71	78	86	95
87-89	2	4	6	8	10	12	14	16	19	22	25	28	31	34	38	43	49	54	60	67	74	81	89	99
90-92	2	4	6	8	10	12	15	17	20	23	26	29	32	36	40	45	51	56	62	69	76	84	93	100
93-96	2	4	6	8	11	13	15	17	20	24	27	30	33	37	42	47	53	58	64	72	79	87	96	100
97-100	2	4	6	9	11	13	16	18	21	24	28	31	35	38	43	49	55	60	67	74	82	90	100	100

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[1] Adapted from "Wildland Fire Danger Rating" Pacific Southwest Forest and Range Experiment Station.

Going now to the other part of the index concerning number of fires, or actually ignition probability since we have eliminated risk from consideration by regarding it as a constant, we see that we are concerned with weather, fuel and fire brand characteristics. Because we have already specified the fuel conditions for the spread and intensity index in order to simplify our end product we can use the same specifications again at this point so as not to reintroduce the fuel variable.

By "fire brand characteristics" we mean the dimensions of the firebrand, whether it is flaming or glowing, and the length of time it will remain a firebrand. If we have a very large firebrand, such as a burning house, airplane or car on a given fuel bed it is almost certain to start a fire if burning conditions are such that the fire can spread beyond the effect of the initial heat source. For such firebrands then we will have 100% chance of ignition within the range of environmental conditions where we need be concerned about fire. In such case the ignition probability becomes a constant and hence would not be of concern to the index we are developing. If we consider successively smaller firebrands, however, environmental conditions at which ignition will take place 100% of the time must become more and more favorable. If we specify that the firebrand that is being considered in our index is very small, as many of the firebrands with which we are concerned are, then we can measure a greater part of the variation in fire danger likely to be experienced in actual practice. Thus we can specify the firebrand characteristic and this does not add to the measurements needed to obtain our final index.

Experience and research has also shown us that one of the most important factors in probability of ignition is the moisture content of fine fuels. With small firebrands the probability of ignition increases rapidly as the moisture content decreases. Since we already have fine fuel moisture as a factor in rate of spread we can use this in our probability of ignition index without adding to the measurements that need to be made.

Temperature is another factor that appears to have considerable effect on the probability of ignition and we will need to include this factor in deriving an index of ignition probability.

Table IV shows an actual ignition probability index using fine fuel moisture and air temperature as controlling factors. The values in the body of the table indicate the relative chance of a small firebrand starting a fire for various combinations of fuel moisture and air temperature.

We have now reached a point in the development of our fire danger rating where we have a measure of the effect of rate of spread and rate of combustion on the control job and a measure of the probability of ignition. The next step is to combine these two measures into a single index. Because we have considered risk constant the index of probability of ignition is also an index of number of fires. Looking at our fire danger structure diagram (Fig. 10) we see that the number of fires branch is not combined with the damage branch where our rate of spread and combustion indexes lie until the final step in getting total fire danger. It is permissable, however, to combine partial indexes in different branches of the fire danger structure as long as logical meaning can be assigned to the resulting index and mathematical or physical laws are not violated in the procedure. Our burning index as set up is a measure of the job load for a single fire while our ignition probability index indicates the probable number of fires. Multiplying the two indexes together then will give a measure of the total job load -- under our specified conditions. This final index which we can designate as the "Job Load Index" accomplishes the objective of our danger rating system -- a measure of the varying job load with changes in weather and fuel moisture conditions.

Table V illustrates a job load index obtained by combining Tables III and IV. This table was not set up by directly multiplying the two tables together. To have done so would have resulted in a table of very large numbers (maximum 100 x 100 or 10,000) which would be awkward in practical use. Instead Table IV was first divided by a constant (60 in this case) and the resulting table multiplied by Table III. The table obtained by this operation was then multiplied by another constant to bring the maximum value down to 100. This procedure maintained the same relative value of the blocks within Table V as would have been obtained in direct multiplication of Tables III and IV, while reducing the index scale to a range of 0 to 100. The selection of 60 as a constant was arbitrary and was actually the average ignition probability index of the area in which the index was to be used. Use of this value as a constant had the effect in Table V of raising the burning index when the ignition index was above average and reducing it when the index was below normal.

The complete fire danger rating index is shown in diagrammatic form in Figure 11.

TABLE IV

IGNITION PROBABILITY INDEX[1]

Dry bulb temperature °F	Fine fuel moisture													Over
	01.5	02.0	02.5	03.0	04.0	05.0	06.0	07.0	08.0	09.0	10.0	11.0	12.0	12.0
Up to 39	81	78	73	68	59	50	40	31	21	12	3	1	0	0
40-44	83	79	74	69	60	51	41	32	22	13	4	1	1	0
45-49	85	80	75	70	61	52	43	33	24	14	5	1	1	0
50-54	86	81	76	71	62	53	44	35	25	15	6	1	1	0
55-59	87	82	77	73	64	55	45	36	26	17	8	1	1	0
60-64	89	83	78	75	65	56	47	37	28	19	10	2	1	0
65-69	90	85	80	76	66	57	48	38	29	20	11	2	1	0
70-74	92	86	81	77	67	59	49	39	30	21	12	2	1	0
75-79	94	88	83	79	69	60	50	40	31	22	13	3	1	0
80-84	95	89	85	81	71	62	52	41	33	24	15	5	1	0
85-89	95	90	86	82	72	63	53	43	34	25	16	6	2	0
90-94	96	92	87	83	73	65	55	44	35	26	17	7	2	0
95-99	97	93	89	85	75	66	56	46	37	27	19	9	2	0
100-104	98	95	90	86	76	67	57	47	38	29	20	10	2	0
105+	100	96	91	87	77	68	58	49	40	30	21	11	3	0

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[1] Adapted from "Wildland Fire Danger Rating" Pacific Southwest Forest and Range Experiment Station.

TABLE V

FIRE LOAD INDEX[1]

Ignition Index	Burning Index 0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	90-94	95-100
0-4	0	0	0	1	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
5-9	0	1	1	2	3	3	3	4	5	6	6	6	6	7	8	9	10	10	11	11
10-14	1	2	2	3	4	5	6	7	8	9	10	10	11	13	14	15	16	17	18	19
15-19	1	2	3	5	6	7	8	10	11	13	14	16	18	18	20	21	23	24	26	27
20-24	1	3	5	6	8	9	11	13	14	16	18	21	23	24	26	27	29	30	32	34
25-29	2	3	5	8	10	11	14	16	18	21	23	24	27	29	31	34	36	37	40	42
30-34	2	3	6	9	11	13	16	19	21	24	27	29	32	34	37	40	42	45	48	50
35-39	2	5	6	10	13	16	19	23	26	27	31	34	37	40	43	46	48	52	55	58
40-44	2	5	8	11	14	18	21	25	29	31	35	39	42	45	48	52	55	60	63	66
45-49	2	5	10	13	16	20	24	28	32	35	39	43	47	50	54	58	62	66	70	73
50-54	2	6	10	14	18	23	27	31	35	39	44	48	52	56	60	64	69	73	77	81
55-59	2	6	11	15	20	25	29	34	39	43	48	52	56	61	66	71	76	80	84	89
60-64	2	7	12	17	22	27	32	37	42	47	52	56	61	67	72	77	82	87	92	97
65-69	2	8	13	18	24	29	34	40	45	50	56	61	66	72	77	83	89	94	100	100
70-74	2	8	14	20	26	31	37	43	48	54	60	66	72	77	82	89	95	100	100	100
75-79	3	8	14	21	27	34	40	46	52	58	65	71	77	84	89	95	100	100	100	100
80-84	3	10	16	23	29	35	42	49	56	62	69	76	82	89	95	100	100	100	100	100
85-89	3	10	16	24	31	37	45	52	60	66	73	80	86	93	100	100	100	100	100	100
90-94	3	10	18	26	33	40	47	55	63	70	77	84	92	100	100	100	100	100	100	100
95-100	3	11	19	28	35	43	52	60	68	76	84	92	100	100	100	100	100	100	100	100

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[1] Adapted from "Wildland Fire Danger Rating" Pacific Southwest Forest and Range Experiment Station.

R-5 system In this system Risk is figured constant

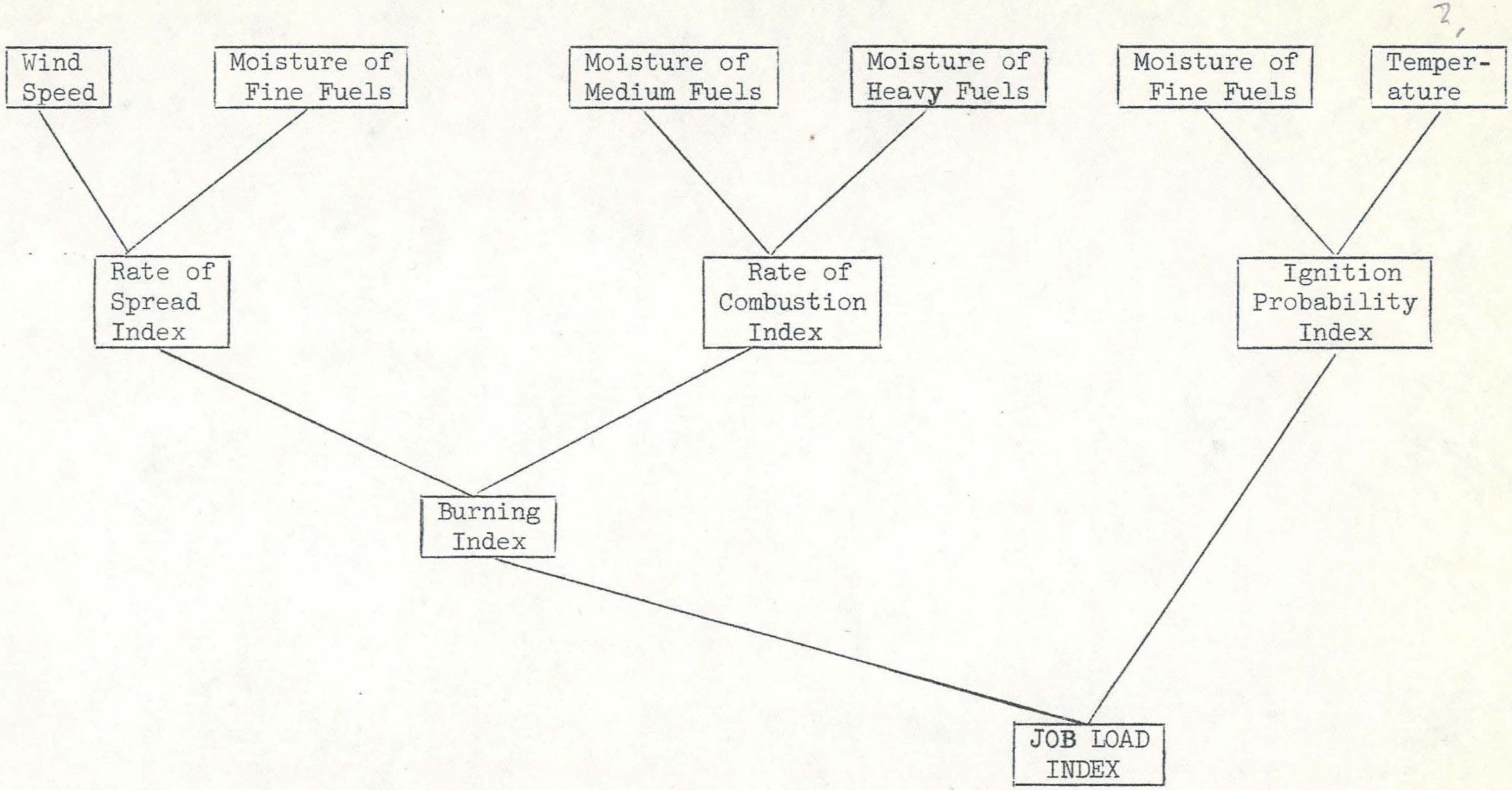
Wind Speed
Moisture of Fine Fuels
Moisture of Medium Fuels
Moisture of Heavy Fuels
Moisture of Fine Fuels
2,
Temperature
Rate of Spread Index
Rate of Combustion Index
Ignition Probability Index
Burning Index
JOB LOAD INDEX

Figure 11. Diagram of fire danger rating system for evaluating changes in fire control job with changing burning conditions.

Errors in Fire Danger Rating Systems

Earlier in the discussion it was brought out that by specifying certain factors and components as being constant introduced some degree of error into the system. This results because these items, although considered as constant in the development of the index, actually do vary, particularly under some conditions. Let us look now at the nature of these errors, how the effect of the errors can be minimized, and how the danger index must be interpreted.

One of the factors we considered as constant was topography. Timewise this factor doesn't vary as far as fire control is concerned, but spatially it can vary a great deal--particularly in mountainous country. Fuel factors other than fuel moisture such as kind, amount, distribution, size, etc. also have large spatial variations. Weather changes, too, seldom occur simultaneously over large areas but progress more or less gradually across an area. Rates of change of fuel moisture even for fuels in the same size classes can be quite different for different fuel types. Wind speed changes can also vary by fuel types as well as by area.

Another source of error is in the way we must measure the variables used in the index. We know that weather and fuel moisture factors vary widely over an area. To obtain a true average value for a given area would require measurements to be made at a great many points within the area. This would be impractical. We must therefore resort to a sampling procedure, whereby the variables are measured only at a very few stations scattered throughout the protection area. Although these stations are located as much as possible at sites that will be representative of the area as a whole, it is inevitable that the conditions at specific points will vary from the fire weather stations.

Still another source of error, briefly mentioned before, is in the kind of basic data available for deriving the relationships between the fire danger factors used as variables and the components of danger evaluated. Best data for this purpose are those derived from controlled experiments. With these data the level of all of the factors is known and the relationships derived represent the true relationships between the factors and the danger components for the specified conditions of the test--within the limits of the accuracy of the experiment. One of the chief drawbacks of this kind of data is its scarcity and that available is usually for only a limited range of conditions.

Empirical data taken from weather and fire reports are subject to a number of errors. The accuracy of the numerical data itself is usually poor. Weather observations must usually be taken from stations nearest to the fire and this may or may not represent the actual conditions at the fire site. Information on many environmental conditions are not available at all. Measurements of fire behavior are seldom made and data on the fire reports usually represent estimates made some time after the fire is out. Rate of spread data taken from routine fire reports has been demonstrated to be hopelessly inaccurate in many cases. Many of the errors in such empirical data are random, however, and if a large enough mass of data is used the individual errors tend to cancel each other so that the relationships derived may be reasonably close to the actual average for the area. To obtain a sufficient mass of data usually requires that it be taken from a rather large area. If conditions are variable over the area then deviations from the average relationship for specific points within the area can be quite large. It should also be emphasized that relationships derived from such data represents the average for the area from which the data were taken only. Because of the large number of factors of unknown quantity usually involved in data taken from weather and fire reports the relationship may bear little resemblance to the true relationship of the fire danger factor to the danger component. Application of the relationship to areas outside that from which the data were taken is of questionable practice. Danger rating systems built on such data are thus of necessity provincial in nature and often of limited accuracy.

Relationships derived from experimental data under a given set of conditions are also subject to error when applied directly to areas where conditions are different from those under which the relationship was obtained. There is a technique available, however, whereby this error can be greatly reduced. To illustrate let us use our rate of spread index. Assume that the relationships of wind speed and fuel moisture to rate of spread were derived from controlled tests. The relationships then represent the true relationship of these factors to spread for the conditions of other factors in the tests. It is reasonable to assume, however, that under another set of conditions these relationships will be the same relatively although not numerically. That is if a change in wind speed from 5 to 8 m.p.h. in the tests resulted in doubling of the rate of spread say from 4 to 8 chains per hour for a given fuel size then the same change in wind speed for some other fuel size might be expected to change rate of spread from 2 to 4 chains per hour. Using this concept we can apply our rate of spread index to any specific point to obtain the relative change in rate of spread with change in wind speed and fuel moisture. Since we are using the relationship as a true relationship of wind speed and fuel moisture to rate of spread it becomes universal in nature and there are no restrictions as to the area to which it can be applied. This in turn provides a tool by which we can reduce the error created by the actual variation in the factors it was necessary to specify as constant. By subdividing the area for which the index is being developed into smaller areas where topography, fuels and weather changes are more uniform we can apply the index independently to these areas. Thus the error induced by the specifying spatially variable factors as constant can be reduced to the extent it is practical to subdivide the area into smaller units for application of the index. By using the relationship as a true one there are no temporal restrictions on the use of the index as long as the measurements of wind speed and fuel moisture represent the conditions for time for which the index is applied. The procedure is subject to error to the degree that our basic assumption that the derived relationships for one set of conditions is relatively the same for any other set. This error is likely to be far less than using the average relationship necessary when the relationships are derived from empirical data--particularly with the advantage of applying the relative value to more uniform areas.

Care must be used in the interpretation of the danger index under this relative relationship concept. Applied to the burning index or fire load index we have developed we cannot use the indexes to compare actual job loads between two specific areas unless all conditions are exactly alike. They can be used only to evaluate the relative change in job load at some specific point with changing levels of the variables we have used.

The danger index meets the objective of the system that we set at the beginning, however, that of measuring the change in job load with changes in burning conditions for a basic fire control organization already established. The index measures the relative change in job load at any point and hence measures the relative change in job load over the area as a whole. Since the basic organization was established at some given strength to take care of fires at a set level of burning conditions the index provides a guide as to how the relative strength of the organization must be varied for other burning conditions.

Fire Danger Rating Scales

Another facet of fire danger rating of importance in the interpretation of fire danger is the scale on which the rating is based. In danger rating the operational rating seldom, if ever, appears as a series of absolute values but is instead converted to an index. This is done by first selecting a set of conditions as the worst probable. The absolute value for these conditions is then determined. This value becomes the base of the index and all lesser conditions expressed as a ratio to this number. The base value can be assigned any numerical value desired. The numerical value usually chosen, however, is 100 so that the index will be on a 0 to 100 scale. In our rate of spread index for example, a wind speed of 25 m.p.h. and fine fuel moisture of 1 percent might be selected as worst probable. Assuming the actual rate of spread for these conditions is 18 chains per hour this absolute value would be assigned a value of 100. If then from the derived relationship of wind speed and fuel moisture to rate of spread a wind speed of 20 m.p.h. and fuel moisture of 2 percent would give a spread of 15 chains an hour the spread index for this second condition would be 83 since the ratio of 83 to 100 is the same as 15 to 18. This same procedure would be used for all combinations of wind speed and fuel moisture needed in the index. If a base value of 200 had been assigned to the absolute value of 18 chains per hour, then the 15 chain rate would have an index value of 166. Likewise, a base of 10 would result in an index of 8.3 for the second condition.

When the absolute values are changed to index numbers, the scale automatically becomes linear. In our job load index then the same change of value in the index indicates the same relative change in job load no matter in what part of the scale the change occurs. That is a change of say 20 to 25 in the index means the same relative change in the job load as a change in the index of 70 to 75. Thus we know that a change of 20 percent in the index also means a change of 20 percent in the job load any place in the index. This feature makes for easy evaluation of the changes in job load with changes in the job load index.

If we compute any of the fire danger indexes for a number of seasons, we can determine the frequency of occurrence of each of the index numbers. By plotting the index number over their frequency we can obtain a "frequency curve" of the job load index. In statistical terminology a "normal" frequency curve is a symmetrical, bell shaped curve with its peak at the middle of the frequency scale. Because of the way fire weather patterns occur a frequency curve of danger indexes doesn't follow this normal form. At the low end of the scale the frequency curve approximates the normal curve. The peak of the curve, however, occurs in the lower range of values with a long "tail" reaching to the high end of the scale.

This indicates that most indexes occur in the lower range of values with relatively few occurrences of indexes in a wide range covering the rest of the scale. For example, in California where a linear scale of 0 to 100 is used the most frequent burning index (peak of curve) is only 11.

To some students of fire danger rating this "skewed" frequency distribution with a peak in the lower range of the scale represents an unnatural situation since they have been schooled to the idea that the most frequent or "average" value should occur near the middle of the scale. To "normalize" the distribution the danger index scale is sometimes adjusted so that the peak does fall near the center. This procedure destroys the linearity of the scale so that changes in one part of the scale no longer means the same change in job load as changes in another part. In the example we used earlier a change of 20 to 25 in the index represents far less change in the job load than a change of 70 to 75. The non-linear scale makes it very difficult to interpret the relative meaning of changes in the danger index unless a scale is set up to show the relation of the job load to the index. In effect this latter scale changes the non-linear scale back to a linear one so we are then right back where we started. The non-linear scale has another undesirable effect. It emphasizes the changes in the lower end of the scale where such changes are relatively unimportant de-emphasizes the changes in the upper ranges where they are of great importance in fire protection.

Non-linearity of scale is sometimes difficult to detect when only the final index table is available or the index appears on a slide rule or computing wheel. However, if the index includes within its range the worst conditions likely to occur in the area and the average condition falls near the middle of the scale it is virtually certain that the index scale is non-linear.

Fire Danger Adjectives

Any discussion of fire danger rating theory would not be complete without some mention of adjective ratings. In most danger rating systems the numerical index scale is divided into classes and some adjective description such as low, moderate, extreme, etc. The divisions of the scale into these classes is done arbitrarily and there is usually little uniformity between systems in the number of classes and what they mean in terms of fire behavior and control.

One reason for this disparity lies in the nature of adjective classifications. When we use an adjective to describe some state or condition we usually describe it in reference to its normal or most frequent state within our own range of experience. Thus when we describe a day as being "hot" we apply this term because the day is warmer than the usual day experienced. The base of experience can be quite different--a hot day to someone who has always lived in coastal Alaska may mean something quite different in actual temperature than a hot day to someone who has spent his life in the Imperial Valley of California. It is hence important that we know the base of experience when comparing adjective ratings. What is considered "extreme" fire danger in one part of the country may represent only relatively moderate burning conditions in another section.

One way by which adjective ratings can be set up in a uniform manner is through the use of a frequency distribution of the danger ratings. In this method a curve is developed to show the average frequency of occurrence of each danger rating value for the area in which the adjectives are to be used. The time period used in the frequency computation should also coincide with the period of use. It is often advantageous to develop the frequency distribution as a cumulative curve with the frequency expressed in percent of the total number of occurrences. A curve of this type is shown in Figure 12.

The number of adjective classes wanted is next determined and some percent of days of the fire season is assigned to each class. The burning index range that will include this percentage of days can then be determined from the frequency curve.

An example of an adjective system using five classes and developed from the frequency curve in Figure 12 is shown in Table I.

Table I

Adjective Class	% of Days	B. I. Range
Low	5	0 - 5
Moderate	45	6 - 11
High	35	12 - 18
Very High	12	19 - 26
Extreme	3	27 -

The percent of days in each class is arbitrary as is the selection of number of classes. However, this system provides a quantitative way of setting adjective ratings and provides a significant statistical measure.

Some Advantages of Multiple Basic Index System of Danger Rating

While our danger rating system was developed for one specific purpose, that of evaluating the relative size of the fire control job with changing burning conditions, the system has the flexibility that permits it to be adapted to other purposes. All of the subindexes--rate of spread, rate of combustion, and ignition probability--that were used in deriving the final danger rating index are available as building blocks to be used singly or put together in various combinations. Thus we may determine the relationship of fire prevention needs to each of the three basic indexes to get a fire danger rating guide to prevention action. The indexes can also be used individually to set limits of conditions for safe and effective prescribed burning.

Because the indexes are based on true relationships, not averages, the uses of the indexes are limited only by the restrictions on their interpretation imposed by the assumptions and specifications necessary in their derivation. The indexes thus have universal application.

Since the danger rating system follows the basic structure of total fire danger the system can be readily enlarged to include more components of fire danger whenever the need arises. The use of true relationships in the system also allows the substitution of improved relationships as they become available through research without altering the basic structure of the system. One of the principal aims of fundamental research in wildland fire is to determine the relationships between the fire danger and the fire danger components. The multiple basic index concept of fire danger rating provides an important and often the only means of putting new knowledge in this field into practical application.

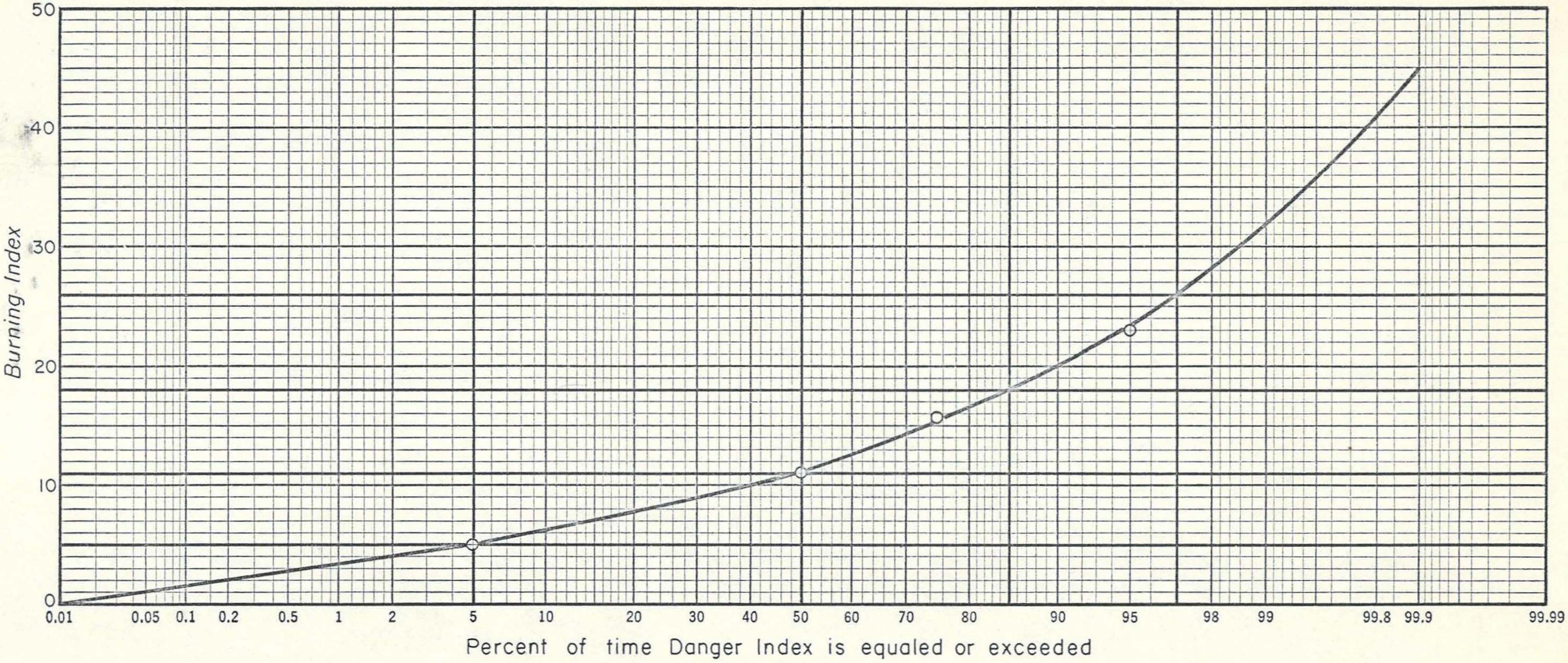

Figure 12.--Frequency of occurrence of burning indexes.